Appendix C
FIELD CALIBRATION AND QUALITY ASSURANCE PROCEDURES FOR ACOUSTIC MULTIBEAM SYSTEMS

C-1. Purpose. This appendix provides recommended technical guidance for performing quality control calibrations and quality assurance tests of multibeam sonar systems used on Corps navigation projects.

C-2. References.

a. Field Procedures for the Calibration of Shallow Water Multibeam Echo-Sounding Systems, André Godin, Canadian Hydrographic Service, February 1996.

b. HYPACK User's Manual, Coastal Oceanographics, Inc., 1998.

c. Multibeam Surveying Workshop Proceedings, U.S. Army Corps of Engineers and NOAA Surveying, Mapping, and Remote Sensing Conference, St. Louis, MO, 19 Aug 1997.

C-3. Background. Field calibration requirements for multibeam systems are significantly more difficult and demanding than those required for single beam echo sounders. Periodic, precise calibration is absolutely essential in order to assure multibeam derived elevations meet the prescribed accuracy tolerances for the project--especially at the outer beams of the array where refractive ray bending and vessel alignment and motion variations can significantly degrade the data quality. Multibeam system sensor alignments and measurement corrections must be periodically aligned, calibrated, tested, and monitored in order to insure data quality. Procedures for performing these calibration and quality control processes are detailed in the referenced publications, and in the manuals provided with the individual sensors making up a multibeam survey system.

a. At present, USACE districts have acquired two different types of multibeam transducers - the Reson Seabat and the Odom Echoscan multibeam systems. In addition, the most commonly used navigation, data acquisition, calibration, and editing software are HYPACK (Coastal Oceanographics, Inc.--reference C-2b) and Triton Elics (TEI) Bathy Pro. This appendix describes the calibration procedures currently employed for these these multibeam systems and software packages; in conjunction with methods developed by the Canadian Hydrographic Service (CHS) and University of New Brunswick. Other multibeam systems, such as Simrad EM3000, Simrad EM950, Atlas STN Fansweep 20 or 15, and Elac Bottomchart Compact, may need other calibration procedures.

b. It should be strongly emphasized that the software and procedures for calibrating, editing, and thinning multibeam data are still being refined and will undergo modifications as new data is acquired and performance is validated. Likewise, the overall accuracy and object detection performance capabilities of multibeam systems are still being assessed. Therefore, any recommended procedures outlined in this appendix must be considered as interim.

C-4. Multibeam Calibration, Quality Control, and Quality Assurance Requirements. There are distinct calibration, QC, and QA procedures that must be performed in order to effectively operate a multibeam system. These include acoustic refraction measurements (i.e., velocity casts and bar checks), system latency calibrations (time variances between positioning, depth, and motion sensors), vessel motion sensor calibration (roll, pitch, and heave sensors), and various other vessel alignment and coordinate/datum corrections. Some calibrations are performed during initial equipment installation on the vessel; however, others must be performed on a more frequent basis--especially when dredging measurement and payment surveys are involved. A summary of measurement and calibration requirements is contained in Table C-1 at the end of this appendix. Failure to perform adequate calibration may render a survey invalid. The following breakdown of calibration tests is taken primarily from Godin (reference C-2a) and HYPACK (reference C-2b) manuals.

a. Sensor Alignment and Offset Measurements. Alignment and offset parameters must be measured for the various sensors making up the multibeam system, e.g., gyro alignment/offsets, transducer mounting angles/offsets, DGPS antenna offsets, static and dynamic drafts, vessel settlement/squat, and estimated latencies. These measurements are made upon initial installation or upon replacement, removal & reinstallation of a sensor. Alignment and offset corrections are typically entered in the software system setup modules--e.g., HYPACK Device Setup or Triton Isis Sonar Setup.

b. Patch Tests/Residual Bias Calibration. Patch Tests are performed after initial installation, and periodically thereafter if sensors are modified, to quantify any residual biases from the initial system alignment. During this calibration series, four separate tests are performed to determine residual alignment biases for:

- Position Time Delay (Latency)
- Pitch Offset
- Roll Offset
- Yaw/Azimuthal Offset

The above parameters are tested, quantified, and updated using commercial software Patch Test routines.

c. Bar Checks. Traditional bar checks under the center beam must be performed to quantify any draft or index errors in the system.

d. Velocity Profile Corrections. Sound velocity profile calibrations are critical--in particular for the outer portion of the beam array. Velocity calibrations shall be performed periodically during the day, and no less than twice per day, and at more frequent intervals or locations in a project if physical changes in the water column (e.g., temperature, salinity) are impacting data quality. The quality of velocity data may be subsequently assessed through use of the "Performance Test" which compares overlapping survey data models. Beam angles shall be reduced below the maximum limits specified in Appendix A if velocity data and/or performance tests indicate uncertainty in outer beam depth measurements. Velocity profile data is entered into the system such as under the HYPACK Sound Velocity Program section.

e. Quality Assurance Performance Test. A performance test is a quasi-independent test used to assess the quality of data being collected, and to verify conformance with the prescribed accuracy specification or object detection requirements for the project. A performance test typically compares overlapping data sets from two different multibeam surveys. This test could also be performed by comparing multibeam data with that collected by another single beam echo sounder. Other comparison test methods are also used, such as matching multibeam bathymetry of a flooded Corps lock chamber against topographic data measured in the same lock chamber during a dewatered state. Object detection capabilities should also be verified by sweeping over simulated objects of known size; placed either in open water or controlled lock chambers. These tests should be periodically performed as a QA check on the overall system performance. A performance test failure indicates the system parameter alignments, offsets, or velocity profiles are invalid, and must be retested. Performance data reduction, processing, and statistical analysis should be performed in near real-time--preferably on board the survey boat. They should be conducted before a critical dredging measurement and payment survey project; however, they are not needed prior to individual surveys in that project. The frequency which performance tests are conducted is a function of past system performance, as evaluated by the field system operator. Therefore, no rigid guidance is prescribed--performance tests may be required weekly, monthly, quarterly, or less frequently, depending on the long-term stability of the results, variations in different project areas, etc. See Table C-1 for recommended allowable tolerances.

f. Real-Time Quality Assurance Tests. This simply involves operator assessment of data quality as it is being collected, making visual observations of cross-track swaths (i.e., noting convex, concave, or skewed returns in flat, smooth bottoms), data quality flags/alarms, or noting comparisons between adjacent overlapping swaths or between independent single beams. Real-time software must have features that allow some form(s) of real-time quality assurance assessment, and performing immediate corrective actions. An alternative quality control assessment is a traditional bar check of individual beams--see reference C-3c.

g. Criteria. Table C-1 contains recommended minimum requirements and tolerances for each of the above tests. Since many of the alignment and offset parameters are interrelated, failures at one level of test may require recalibration and/or retesting prior levels. The remaining sections in this appendix provide more detail on technical procedures for performing the individual tests. The referenced publications or manufacturer's operation manuals should be consulted for more details.

C-5. Coverage of Multibeam Systems. The coverage of multibeam systems is a function of swath width and water depth. Most systems provide coverage of two to approximately seven times the water depth. The number of individual beams (and footprint size) within the swath array varies with the manufacturer. The outer beams on each side of the swath are subject to more corrections and may not be useful. The maximum angular extent of coverage must be verified, and accordingly restricted, by conducting some form of independent performance test. Due to the increased density of soundings with multibeam systems, it is possible, with proper calibration and adjustments, to detect and resolve smaller objects on the bottom relative to single beam systems. However, this detection capability may be reduced due to larger footprints in the outer beams.

C-6. Error Sources in Multibeam Systems. Several sources of errors and biases exist in multibeam surveying which are not found in single beam surveying. With improved resolution and coverage comes the need for much greater control and calibration to ensure that the sounding is recorded from the correct position on the sea floor. This is accomplished by using a high accuracy differential GPS system, heave-pitch-roll (HPR) sensor, and a gyrocompass. In addition, the time synchronization for all these components is critical. For this reason, the system accuracy is comprised not only of the multibeam sonar accuracy but also these various components which make up the total system. Some of the more significant error components include:

a. Static offsets of the sensors. These are the distances between the sensors and the reference point of the vessel or the positioning antenna.

b. Transducer draft. This is the depth of the transducer head below the waterline of the vessel. As in single beam systems, standard bar checks are performed to measure static and dynamic draft variations.

c. Time delay between the positioning system, sonar measurement, and HPR sensor. This delay or latency must be accurately known and accounted for in the processing of the hydrographic data.

d. Sound velocity measurements. The velocity of sound in the water column must be accurately known so the correct depth can be measured.

e. The acceleration and translation measurements of the HPR. These measurements are critical for corrections to the vessel’s roll and pitch.

These parameters must be measured and corrected in the multibeam sonar system. These corrections must be performed in the field, not in a post-processing environment. Commercially available software is designed to process and accommodate these inputs, offsets, and corrections.

C-7. Initial Installation Alignment and Static Offset Measurements. This is the process of physical measurement and alignment of the vessel platform, transducers, gyrocompass, and HPR sensor. This measurement should be performed with the vessel stabilized on a trailer or on blocks where more exact measurements can be made. This will minimize errors in positioning of the sensors and, with the proper offsets applied, the static corrections will be reduced. The sensors should be measured from a reference point in the vessel. This point is typically the center of gravity or the intersection of the pitch and roll axis. The center of gravity will change with varying load conditions of the vessel and thus must be chosen to represent the typical conditions while surveying. On large stable vessels, the center of gravity will slightly change vertically along an axis that contains the center of buoyancy. On smaller vessels, the center of gravity and the center of buoyancy may not be exactly aligned due to eccentric loading. This condition is to be avoided as it also contributes to the instability of the vessel itself. This information can be obtained from the blueprints of the vessel. This reference point (now the coordinate system origin) should be a place which is easily accessible and from where measurements to the sensors will be made. The coordinate system should be aligned with the x-axis along the vessel keel, the y-axis abeam the keel, and the vertical (z-axis) positive up. The offsets of the sensors are measured from the reference point to the center of the sensor. The center of the sensor can be found in the manufacturer's schematic of the sensor or can be accurately measured with a survey tape. It is common for the acoustic and physical centers to be in different places (e.g., Simrad EM 3000). The magnitude and direction of the measurement should be verified and recorded.

a. HPR Sensor. If possible, the HPR sensor should be placed on the centerline of the vessel as close as possible to the center of gravity or the intersection of the roll and pitch axes of the vessel. (The TSS DMS-05 allows heave high pass filtering at a remote location). If possible, use the same mount angles as used for the transducer. The x-axis of the HPR should match the x-axis of the transducer. Azimuthal misalignment of the HPR will result in the depth measurements being in error proportional to the water depth. Misalignment of the HPR sensor in yaw causes a roll error when pitching, and a pitch error while rolling. (If the transducer and HPR are collocated (e.g., Odom Echoscan), many alignment corrections become far less critical).

b. Transducer. The multibeam transducer should be installed as near as possible to the centerline of the vessel and level about the roll axis. It should also be aligned with the azimuth of the vessel. This alignment is critical since there is no beam steering with either the Reson Seabat or Odom Echoscan. There is, however, beam steering with the Simrad transducers about the y-axis. (The EM 950/1000 is steered in roll, EM 3000 is steered in pitch, and the EM 300 is steered in roll-pitch-yaw).

(1) Most multibeam transducers used on smaller USACE vessels are mounted over-the-side on a shaft and boom device. (Norfolk and New York Districts 65-foot vessels have hull-mounted transducers). With this type of mount, it is imperative that the azimuthal alignment between the transducer and keel be as accurate as possible. This can be accomplished with the vessel on a trailer or blocks on land and using standard surveying and leveling techniques. Since this boom mounted technique allows for raising the transducer at the end of each day of operations and lowering it at the start of the next day’s survey, this type of mount should be periodically checked for correct alignment. The frequency with which it is checked will depend on what type of surveying is performed and under what conditions. Hull mounted transducers are generally fixed in place and will not need to be checked as frequently.

(2) The angle of the transducer mount must be determined and recorded, unless the HPR is collocated. Since most vessels underway will be lower in the stern, the transducer will generally need to be rotated aft to compensate for this angle. The patch test will also check for the transducer angle. The resulting beam should then project normal to the sea floor while conducting surveying operations.

c. Gyro. The gyro should be aligned with the x-axis of the vessel using an electronic total station and geodetic control points. This can be done with the vessel on a trailer or secured tightly against a pier where there is minimal wave action. The gyro should be warmed up and, if necessary, the proper corrections for latitude applied. Locate two points on the centerline of the vessel and position a target on each of them. Observe the two targets with the total station and synchronize the readings with the gyro readings. Several readings will be needed for redundancy. Compute the vessel’s azimuth and compare with the gyro readings. Compute the mean and standard deviation of the readings. If the offset is more than 1° at the 95%

confidence level, realign the gyro with the centerline and repeat the observations. If less than 1°, apply the correction to the gyro output. This procedure can also be performed using three GPS receivers instead of the total station. The processing may take longer than with the total station.

d. Squat/Settlement Measurement using Transit/Theodolite. The combined squat and settlement of the vessel should be measured at several speeds and a look-up table produced for correcting the transducer draft. This measurement is essential since the HPR will not measure the long-term change in elevation. The sensor will record the sudden change in elevation but the measured heave will drift back to zero. The settlement can be measured with a transit on shore and a 2- meter level rod or stadia board on the vessel positioned over the HPR sensor (i.e., the point where the heave data are low pass filtered). The vessel should make several passes at various speeds in front of the shore station and the rod elevation recorded. The elevation difference at each speed is noted and used as the draft correction while surveying. Be sure the correct sign is applied when entering the correction in the software.

e. Squat/Settlement Measurement using GPS . An alternate method for determining squat/settlement makes use of carrier-phase differential GPS elevation difference measurement.

(1) Position the DGPS antenna near the center of the vessel and measure the vertical and horizontal distance from the antenna to the vessel’s reference point with steel tape.

(2) Use data from a nearby tide gauge to provide a datum from which to measure the elevation. The gauge should be in the survey area and if the area is large, two gauges should be used.

(3) Run the same survey line at different speeds. Also run the line under different loading conditions.

(4) Record the GPS positions, heave, pitch, roll, vessel speed and water levels at common times. The sampling rate should be at the highest for GPS and HPR sensors (10Hz and 100Hz, respectively) while the water levels can be recorded at approximately 5-10 minute intervals.

(5) Record the antenna height while stationary.

(6) All data should be synchronized and interpolated if necessary.

(7) Use the GPS antenna offsets and attitude data to compute the roll and heave and correct the antenna elevations. Subtract water level data and heave data from GPS antenna elevation.

(8) With these corrections for motion and water levels, compute the average speed in the water and the average antenna elevation with respect to the ellipsoid. Produce a look up table for the transducer draft correction.

Differential GPS may be used to directly reference the absolute vertical position of the multibeam transducer, thus eliminating the need for tide/stage data, squat, dynamic draft, etc. See EM 1110-2-1003.

f. HPR Sensor Time Delay. Time delay in the attitude sensor will result in roll errors, which greatly affect reduced elevations at the outer beams. In addition, horizontal accelerations in cornering can also affect the HPR measurements, which will also result in errors in the depth measurements. Basically, the principle to detect roll errors is to observe, from the bathymetric data, short period changes in the across track slope of the sea floor when surveying flat and smooth areas. Coastal Oceanographic’s HYPACK and TEI's Isis/Bathy Pro programs can be used to check the time delay. HYPACK will process the timing in post-time while the TEI Isis/Bathy Pro displays a real-time confidence check. The Canadian Hydrographic Service and University of New Brunswick have developed UNIX based software to assess time delay in swath data.

g. Positioning Time Delay (Latency). Time delay in the positioning is the time lag between the time positioning data are received and the time the computed position reaches the logging module. This results in a negative along-track displacement of the depth measurements. While surveying at slow speeds, this displacement will be small. In general, the processing time for the position will vary with the number of observations used in the final GPS solution. If the time imbedded in the GPS message will be used, then you must ensure the correct synchronization between this time and the transducer or signal processing clock.

C-8. <u>Patch Test (Residual Bias Calibration)</u>. Patch Tests are periodically performed to quantify any residual biases in the initial alignment measurements described previously. This test (actually a series of reciprocal lines run at varying speeds, depths, and bottom terrain) must be performed carefully to ensure that subsequent data collected when surveying is accurate and reliable. The Patch Test determines (and provide correctors for) the following potential biases: (1) residual pitch offset, (2) residual roll offset, (3) residual positioning time delay, and (4) residual azimuthal (yaw) offset. The determined offsets and delays will be used to correct the initial misalignments and calibrate the system. Each of these bias tests is described below and is summarized in Table C-2 at the end of this appendix.

a. Data Acquisition. Survey quality DGPS positioning instruments must be used when conducting the Patch Tests--especially in shallow draft projects. The weather should be calm to ensure good bottom detection and minimal vessel motions. Since most of the lines to be run will be reciprocal lines, it is important to have capable vessel steering and handling. The lines should be run in water depths comparable to the typical project depths encountered. The order the lines are run is not important although it is recommended that at least two (2) sets of reciprocal lines be run for redundancy. Although the outer beams of multibeam sonar are subject to a smaller grazing angle, these beams should provide good data provided the appropriate corrections are applied from the patch test. Vessel speed should be regulated such that 50% forward overlap is obtained. The maximum speed may be calculated by the following equation:

$$v = S * d * \tan(b/2) \qquad \text{Eq. C-1}$$

where:
- v = maximum velocity (m/s)
- S = sounder sampling rate per second (1/t)
- d = depth
- b = fore-and-aft beamwidth angle

b. Positioning Time Delay Test and Pitch Bias Test. Two or more pairs of reciprocal lines are run at different speeds to check for biases in both positioning time delay (latency) and pitch bias. Latency is determined from runs made over the same line in the same direction, but at differing speeds. (Both these biases may exist simultaneously and must be discerned and separated during the test data processing). These lines should be run in an area with a smooth, steep slope--10° to 20°, if possible. The slope should ideally be at least 200 m long in order to obtain good samples. A channel side slope may have to suffice if no other relief is available . At least two pairs of reciprocal lines should be run both up and down slope, at velocities differing by at least 5 knots to best assess the time delay. Pitch is determined from the runs made over the same lines at the same speed in opposite directions.

c. Roll Bias Test. In an area of flat topography, run at least one pair of reciprocal lines approximately 200 m in length to test for roll biases. Roll bias will best show up in deep water. Depending on the type of multibeam system, these lines should be run at a speed to ensure significant forward overlap of the beam's footprint. The beam width can be found in the manufacturer's specifications.

d. Azimuthal (Yaw) Offset Test. Two adjacent parallel pairs of reciprocal lines shall be run normal to a prominent bathymetric feature such as a shoal or channel side slope, in shallow water. Do not use a feature with sharp edges such as wrecks since there is more ambiguity in the interpretation. The adjacent lines have an overlap of about 15% and the feature should be wide enough to ensure adequate sampling. This width is generally greater than three swath widths. These lines should be run at a speed to ensure significant overlap of the beam forward footprint--use the same equation as that for roll bias.

C-9. Patch Test Data Processing and Adjustment. Commercial Patch Test routines automatically calculate system latencies, roll, pitch, and yaw biases in multibeam data. HYPACK routines will grid the data into 100 cells before any adjustments are made; however, the reduced data set may not be accurately representative of the test lines. The procedure followed by TEI and CHS/UNB uses the entire data set collected from the patch test lines without thinning (i.e., gridding or binning). The reason for this difference is due to the processing speeds of the platforms used (PC vrs. UNIX workstation). Visualization of the bathymetric data is important in both methods. In addition, the position and attitude data should be checked for errors, especially noting the time tag errors. Cleaning of the bathymetry is not necessary since individual soundings will not be adjusted but rather clusters of data points will be analyzed. The procedures to process the Patch Test data should follow the CHS/UNB sequence recommended below. Note that this differs from the sequence recommended by HYPACK: roll-latency-pitch-yaw.

a. Positioning Time Delay (Latency) Bias. This delay is computed by measuring the along-track displacement of soundings from the pair of coincident lines run at different speeds over the steep slope or other prominent topographic feature. Lines run in the same direction should be used so as to avoid the effect of pitch offset errors. The equation to compute time delay is:

$$TD = d_a / (v_h - v_l) \quad \text{Eq. C-2}$$

where:
- TD is the time delay in seconds
- d_a is the along-track displacement
- v_h is the higher vessel speed
- v_l is the lower vessel speed

The survey lines are processed, plotted and compared while assuring that no corrections are made for positioning time delay, pitch error, roll error and gyro. The time delay is then averaged by getting several measurements of the displacement in the along-track direction. This process is performed iteratively until the profiles and contours match or achieve a minimum difference.

b. Pitch Offset Bias. The pitch offset bias is determined from the two pairs of reciprocal lines run over a slope at two different speeds. The important characteristic of pitch offset is that the along-track displacement caused by pitch offset is proportional to water depth. Thus, the deeper the water the larger the offset. The pitch offset can be computed using the following equation:

$$a = \tan^{-1} [(d_a /2) / (\text{depth})] \quad \text{Eq. C-3}$$

where:
- a is the pitch offset
- d_a is the along-track displacement
- depth is the water depth

The lines are processed while only applying the positioning time delay correction and the static offsets of the sensors. The pitch offset is then averaged by taking several measurements of the displacement in the along-track direction. This process is performed iteratively until the profiles and contours match or reach a minimum difference. It should be noted that unless kinematic DGPS positioning is employed, determining d_a to a reasonable level of accuracy is difficult in shallow water.

c. Azimuthal Offset Bias. The same two pairs of lines run adjacent to a bathymetric feature will be used for the measurement of the azimuthal offset. One pair of adjacent lines run in opposite directions is processed at a time to remove any potential roll offset. The azimuthal offset can be obtained from the following equation:

$$y = \sin^{-1} [(d_a /2) / X_i] \qquad \text{Eq. C-4}$$

where:
y is the azimuthal offset
d_a is the along-track displacement
X is the relative across track distance for beam i

The survey lines are processed with only the positioning time delay and pitch offset corrections and static sensor offsets. The azimuthal offset is averaged by several measurements of the displacement d_a over the feature and knowing the across-track distance X at the location of the measurements. This process is performed iteratively until the profiles and contours match or achieve a minimum difference.

d. Roll offset bias. Roll bias is computed using the pairs of reciprocal lines run over a flat, deep area. Generally this offset is the most critical in deeper water and should be carefully measured. For small angles of less than 3° the roll offset can be estimated by the following equation:

$$r = \tan^{-1} [(d_z/d_a) / 2] \qquad \text{Eq. C-5}$$

where:
r is the roll offset
d_z is the depth difference
d_a is the across-track distance

The survey lines are processed while applying the positioning time delay, pitch offset, gyro offset corrections and static sensor offsets. The roll offset is averaged by several measurements of the across track displacement d_a along the test swaths. This process is performed iteratively until the profiles and contours match or achieve a minimum difference.

C-10. Performance Test. Quality assurance performance tests are conducted upon equipment installation or modification or at the beginning of major projects. This test partially checks the parameters and biases that were measured and computed during the above calibrations. The procedure described below compares a check line swath beam with a reference surface model complied from narrowly spaced multibeam data using only near-center beam data, or with single-beam data. It is not truly an independent test, only an assessment indicator. Failure of the performance test survey to meet the recommended tolerances in Tables A-1 and C-1 requires corrective action--i.e., remeasurement, recalibration, patch testing, etc.

a. Reference Surface. This is essentially a small survey run over a flat area in water depths of not more than 30 meters. It represents the "baseline" area. The beams outside about 45-60° swath width should be removed prior to editing. Four parallel lines are run with at least 150% bottom overlap--i.e., 25% sidelap. One should ensure that the inner beams overlap enough to give redundant data. After these lines are run, 4 or 5 parallel lines are run perpendicular to the previously run lines with the same swath and overlap. The speed over the ground should be the same on both sets of lines. A velocity cast should be made in this area and the corrections applied.

b. Check Lines. Multibeam "check lines" will be run such that the full beam array can be tested against the Reference Surface. A pair of parallel multibeam swath lines should be run inside the reference surface. Overlap as described above is not needed. The vessel speed is the same as for the reference surface.

c. Data Processing and Analysis. Performance test data processing should follow the general rules outlined below.

(1) The reference surface should be cleaned of outliers. This should be performed manually and adjustment of positions, attitude and bathymetry be made to ensure clean data. Smoothing, thinning, or binning of data must not be made.

(2) A digital terrain model (DTM) of the reference surface is created from the cleaned data. Then use an averaging gridding algorithm to smooth the data. The gridding size should be no larger than the average footprint of the inner beams or the estimated positional accuracy, whichever is greater. Using large vertical exaggeration, the DTM should be observed on 3D-visualization software.

(3) The check lines are then processed individually and each beam depth throughout the entire array is compared to the reference surface. A difference surface between the reference DTM surface and the check lines is then created and contoured and statistics computed to assess overall performance. From these differences the corrections to the system can be checked against the criteria recommended in Table C-1.

(4) Statistical parameters to be computed and evaluated include:

- Outliers. Depth differences between the check and reference surfaces are computed at each beam point along the check line array. Maximum outliers should not exceed the values recommended in Table C-1. Presence of excessive outliers in the outermost portions of the array indicates calibration/velocity problems, and requires correction and/or restricted beam widths.

- Mean Difference. The difference, or bias, between the reference and check surfaces should not exceed the recommended value in Table C-1. Excessive surface bias errors require immediate assessment and correction.

- Standard Deviation. The standard deviation (95%) of the differences between the reference and check surfaces should not exceed the limit shown in Table C-1--i.e., the prescribed performance accuracy standard for depths given in Table A-1. The existence of excessive outliers and biases will increase the overall standard deviation. Restriction of the beam array angle may reduce this error if most of the excessive outliers are in the outermost portion of the array. Results from this test may be used as an indicator of overall accuracy performance. In order to assess resultant accuracy as a function of swath width, it may be necessary to isolate sections of the beam swath.

C-11. Calibration and Quality Control Documentation. Project or contract files must contain documentary evidence that these calibration tests were performed. This would include a written log (or equivalent digital record) of sensor offset and alignment measurements, patch test calibration results, sound velocity measurements, tide/stage observations, performance test results, and other quality assurance observations, such as bar checks.

C-12. Multibeam Data Processing. Multibeam data is processed and edited on a variety of commercial platforms and software packages. Due to the size of the data sets, numerous thinning or binning methods exist for reducing the data down to manageable levels. The procedures used for such data thinning/binning may adversely corrupt or erroneously warp the reduced model, and could impact dredged volume computations. This could occur if shoal biasing or averaging is used to form a digital terrain model (DTM), digital elevation model (DEM), or triangulated irregular network (TIN)--such biasing processes should be avoided.

C-13. Summary. The above measurement, alignment, calibration tests, and quality assurance procedures are based on procedures currently followed by a variety of government and commercial sources, such as those listed in the reference paragraph. Many of these procedures, and related intelligent data thinning software routines, are being continually updated as new algorithms and performance test techniques become validated. Maintain contact with CETEC-TD-G for updates on current developments.

Table C-1. Recommended Multibeam Calibration Procedures and Criteria

	Frequency of Measurement (Minimum) [1]	Calibration Procedure	Allowable Tolerance (95%)	Corrective Action
SENSOR ALIGNMENT AND OFFSET MEASUREMENTS:				
Transducer	Initial installation	Leveling/Tot Station	0.5 degrees	Remount
Gyro	Initial installation	Self calibration	Manufacturer's specification	Replace
Heave/Pitch/Roll	Start of project	Self calibration	0.1 degree	Remount
GPS Antenna	Initial installation	Leveling	0.1 foot	Remount
Squat	Annually	Transit/level/DGPS	0.1 foot	None
Dynamic Draft	As required	Fixed vessel marks	0.1 foot	None
ACOUSTIC DRAFT AND SOUND VELOCITY MEASUREMENTS:				
Bar Check	Twice daily	Bar ck center beam	0.2 foot	Stop/redo
Velocity Probe	Twice daily or more	Self calibration if conditions require	0.01 m/sec	stop/redo
PATCH TEST (RESIDUAL BIAS CALIBRATION):				
Pitch	Init Install or Mod	2 pairs or reciprocal lines on slope	0.2 feet	apply corr'n in software
Roll	Init Install or Mod	1 pair of reciprocal lines over flat area	0.2 feet	apply corr'n in software
Time Delay (latency)	Init Install or Mod	2 pairs of reciprocal lines on slope	0.2 feet	apply corr'n in software
Azimuth/Yaw	Init Install or Mod	2 pairs of adjacent lines over shoal	0.2 feet	apply corr'n in software
PERFORMANCE TEST (QUALITY ASSURANCE TEST):				
Mean Bias	Start of Major Proj	Run Reference & Check Surfaces	0.2 feet	redo prior calibrations
Standard Error	Start of Major Proj	Run Reference & Check Surfaces	per Table A-1	redo prior calibrations
Maximum Outliers	Start of Major Proj	Run Reference & Check	1 foot	Reduce array

1. Calibration frequency indicated should not be considered absolute as it is subject to local conditions, such as stability of project area, stability between repeated tests, nature of project, etc.

Table C-2. Summary of Patch Test Procedures and Computations

	Posit/Time Delay	Pitch Offset	Azimuth Offset	Roll Offset
LINES REQUIRED	Two (2) on same heading over slope or shoal	Two (2) pairs on reciprocal headings at 2 speeds	Two (2) pairs over bathymetric feature	Two reciprocal lines over flat area
PRIOR CORRECTIONS APPLIED	None--other than static offsets	Positioning time delay	Position time delay and pitch	Position time delay, pitch, &gyro
COMPUTATION METHOD	Average of displacements in along track direction	Average of displacements in along track direction	Average of displace in across track direction	Average of displacements in across track direction
VISUAL METHOD	Match profiles and contours	Match profiles and contours	Match profiles and contours	Match profiles and contours